Chapter 5

Force and Motion

- We have seen that part of physics is a study of motion, including acceleration which are **changes** in velocities.
- Physics also a study of what can **cause** an object to accelerate. That cause is a **force**.
- **Force :** a push or a pull
- **Force is a vector :** it has magnitude and direction.
- **S.I Unit s** : Newton (N)

5-2 Newtonian Mechanics

- The relation between a force and the acceleration it causes was first understood by Isaac Newton (1642-1727).
- The study of that relation, as Newton presented it, is called **Newtonian mechanics.**

5-3 **Newton's First Law**

- Imagine sending a puck sliding over the ice of a skating rink. More the surface is slipper, the puck would slide farther and farther.
- In the limit you can think of a long, extremely slippery surface (frictionless surface), we can conclude that a body will keep moving with constant velocity if no force acts on it.

- **Newton’s First Law :** If a body is at rest, it remains at rest. If it is moving, it continues to move with the same velocity.

5-4 Force

- Since forces are vector quantities, they combine according to the vector rules of chapter 3.
- When two or more forces act on a body, we can find their **net force** or **resultant force** by adding the individual forces vectorially.
- Forces are most often represented with a vector symbol such as $\vec{\boldsymbol{F}}$.
- A net force is represented with the vector symbol $\vec{\boldsymbol{F}}_{\boldsymbol{net}}$.

- The more proper statement of **Newton's First Law** in terms of a net force : **If no net force acts on a body ($\vec{F}_{net} = 0$), the body's velocity cannot change.**

5-5 Mass

- Everyday experience tells us that a given force produces different magnitudes of acceleration for different bodies.
- Put a baseball and a bowling ball on the floor and give both the same sharp kick. The baseball receives a noticeably larger acceleration than the bowling ball.
- Why: Because the mass of the baseball differs from the mass of the bowling ball.

- The mass of the body is the characteristic of that body that relates the body’s acceleration to the net force causing the acceleration.
- In other word **the mass is a measure of how difficult it is to change its velocity.**

5-6 Newton’s Second Law

- The net force on a body is equal to the product of the body’s mass and its acceleration.

$$\vec{F}_{net} = m\vec{a}$$

Which may be written in the component versions:

$$F_{net,x} = ma_x \qquad F_{net,y} = ma_y \qquad F_{net,z} = ma_z$$

Sample Problem

One- and two-dimensional forces, puck

Parts A, B, and C of Fig. 5-3 show three situations in which one or two forces act on a puck that moves over frictionless ice along an x axis, in one-dimensional motion. The puck's mass is $m = 0.20$ kg. Forces $\vec{F}_1$ and $\vec{F}_2$ are directed along the axis and have magnitudes $F_1 = 4.0$ N and $F_2 = 2.0$ N. Force $\vec{F}_3$ is directed at angle $\theta = 30°$ and has magnitude $F_3 = 1.0$ N. In each situation, what is the acceleration of the puck?

KEY IDEA

In each situation we can relate the acceleration $\vec{a}$ to the net force $\vec{F}_{\text{net}}$ acting on the puck with Newton's second law, $\vec{F}_{\text{net}} = m\vec{a}$. However, because the motion is along only the x axis, we can simplify each situation by writing the second law for x components only:

$$F_{\text{net},x} = ma_x. \qquad (5\text{-}4)$$

The free-body diagrams for the three situations are also given in Fig. 5-3, with the puck represented by a dot.

Situation A: For Fig. 5-3b, where only one horizontal force acts, Eq. 5-4 gives us

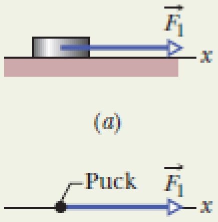
$$F_1 = ma_x,$$

which, with given data, yields

$$a_x = \frac{F_1}{m} = \frac{4.0\text{ N}}{0.20\text{ kg}} = 20\text{ m/s}^2. \qquad \text{(Answer)}$$

The positive answer indicates that the acceleration is in the positive direction of the x axis.

A



The horizontal force causes a horizontal acceleration.

(a)

This is a free-body diagram.

(b)

Situation B: In Fig. 5-3d, two horizontal forces act on the puck, $\vec{F}_1$ in the positive direction of x and $\vec{F}_2$ in the negative direction. Now Eq. 5-4 gives us

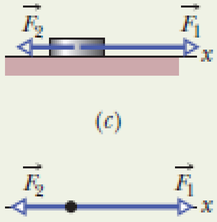
$$F_1 - F_2 = ma_x,$$

which, with given data, yields

$$a_x = \frac{F_1 - F_2}{m} = \frac{4.0\text{ N} - 2.0\text{ N}}{0.20\text{ kg}} = 10\text{ m/s}^2. \qquad \text{(Answer)}$$

Thus, the net force accelerates the puck in the positive direction of the x axis.

B



These forces compete. Their net force causes a horizontal acceleration.

(c)

This is a free-body diagram.

(d)

Situation C: In Fig. 5-3f, force $\vec{F}_3$ is not directed along the direction of the puck's acceleration; only x component $F_{3,x}$ is. (Force $\vec{F}_3$ is two-dimensional but the motion is only one-dimensional.) Thus, we write Eq. 5-4 as

$$F_{3,x} - F_2 = ma_x. \tag{5-5}$$

From the figure, we see that $F_{3,x} = F_3 \cos\theta$. Solving for the acceleration and substituting for $F_{3,x}$ yield

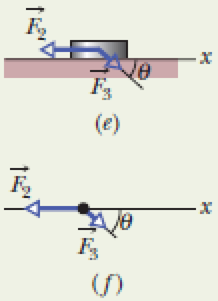
$$a_x = \frac{F_{3,x} - F_2}{m} = \frac{F_3 \cos\theta - F_2}{m}$$

$$= \frac{(1.0\text{ N})(\cos 30^\circ) - 2.0\text{ N}}{0.20\text{ kg}} = -5.7\text{ m/s}^2.$$

(Answer)

Thus, the net force accelerates the puck in the negative direction of the x axis.

C



Only the horizontal component of $\vec{F}_3$ competes with $\vec{F}_2$.

This is a free-body diagram.

Sample Problem

Two-dimensional forces, cookie tin

In the overhead view of Fig. 5-4a, a 2.0 kg cookie tin is accelerated at 3.0 m/s^2 in the direction shown by $\vec{a}$, over a frictionless horizontal surface. The acceleration is caused by three horizontal forces, only two of which are shown: $\vec{F}_1$ of magnitude 10 N and $\vec{F}_2$ of magnitude 20 N. What is the third force $\vec{F}_3$ in unit-vector notation and in magnitude-angle notation?

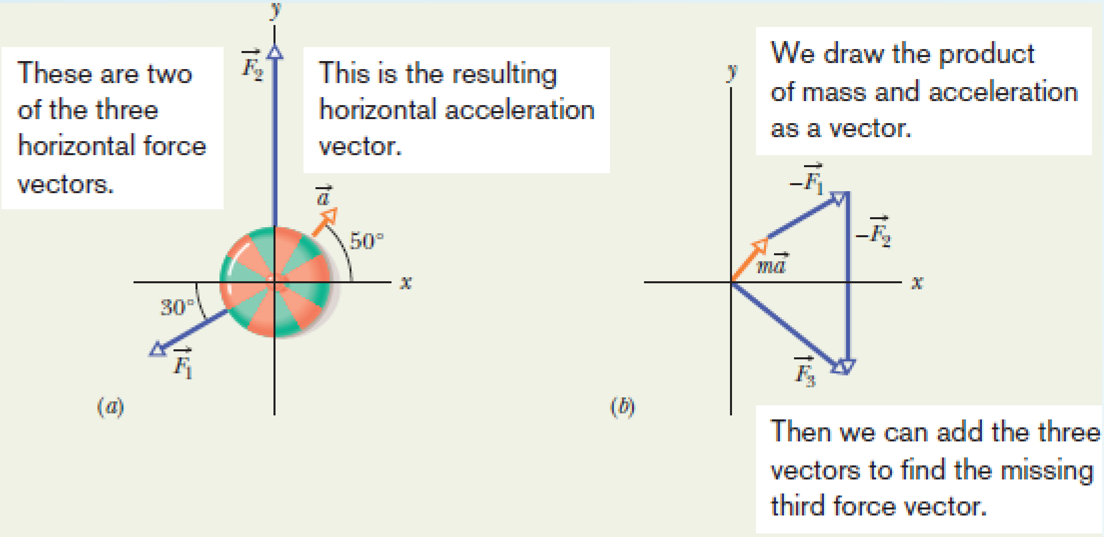
KEY IDEA

The net force $\vec{F}_{\text{net}}$ on the tin is the sum of the three forces and is related to the acceleration $\vec{a}$ via Newton's second law ($\vec{F}_{\text{net}} = m\vec{a}$). Thus,

$$\vec{F}_1 + \vec{F}_2 + \vec{F}_3 = m\vec{a}, \tag{5-6}$$

which gives us

$$\vec{F}_3 = m\vec{a} - \vec{F}_1 - \vec{F}_2. \tag{5-7}$$



These are two of the three horizontal force vectors.

This is the resulting horizontal acceleration vector.

We draw the product of mass and acceleration as a vector.

Then we can add the three vectors to find the missing third force vector.

Fig. 5-4 (*a*) An overhead view of two of three horizontal forces that act on a cookie tin, resulting in acceleration $\vec{a}$. $\vec{F}_3$ is not shown. (*b*) An arrangement of vectors $m\vec{a}$, $-\vec{F}_1$, and $-\vec{F}_2$ to find force $\vec{F}_3$.

Calculations: Because this is a two-dimensional problem, we *cannot* find $\vec{F}_3$ merely by substituting the magnitudes for the vector quantities on the right side of Eq. 5-7. Instead, we must vectorially add $m\vec{a}$, $-\vec{F}_1$ (the reverse of $\vec{F}_1$), and $-\vec{F}_2$ (the reverse of $\vec{F}_2$), as shown in Fig. 5-4*b*. This addition can be done directly on a vector-capable calculator because we know both magnitude and angle for all three vectors. However, here we shall evaluate the right side of Eq. 5-7 in terms of components, first along the *x* axis and then along the *y* axis.

x components: Along the *x* axis we have

$$\begin{aligned} F_{3,x} &= ma_x - F_{1,x} - F_{2,x} \\ &= m(a\cos 50°) - F_1\cos(-150°) - F_2\cos 90°. \end{aligned}$$

Then, substituting known data, we find

$$\begin{aligned} F_{3,x} &= (2.0\ \text{kg})(3.0\ \text{m/s}^2)\cos 50° - (10\ \text{N})\cos(-150°) \\ &\quad - (20\ \text{N})\cos 90° \\ &= 12.5\ \text{N}. \end{aligned}$$

y components: Similarly, along the *y* axis we find

$$\begin{aligned} F_{3,y} &= ma_y - F_{1,y} - F_{2,y} \\ &= m(a\sin 50°) - F_1\sin(-150°) - F_2\sin 90° \\ &= (2.0\ \text{kg})(3.0\ \text{m/s}^2)\sin 50° - (10\ \text{N})\sin(-150°) \\ &\quad - (20\ \text{N})\sin 90° \\ &= -10.4\ \text{N}. \end{aligned}$$

Vector: In unit-vector notation, we can write

$$\begin{aligned} \vec{F}_3 &= F_{3,x}\hat{\text{i}} + F_{3,y}\hat{\text{j}} = (12.5\ \text{N})\hat{\text{i}} - (10.4\ \text{N})\hat{\text{j}} \\ &\approx (13\ \text{N})\hat{\text{i}} - (10\ \text{N})\hat{\text{j}}. \qquad \text{(Answer)} \end{aligned}$$

We can now use a vector-capable calculator to get the magnitude and the angle of $\vec{F}_3$. We can also use Eq. 3-6 to obtain the magnitude and the angle (from the positive direction of the *x* axis) as

$$F_3 = \sqrt{F_{3,x}^2 + F_{3,y}^2} = 16\ \text{N}$$

and

$$\theta = \tan^{-1}\frac{F_{3,y}}{F_{3,x}} = -40°. \qquad \text{(Answer)}$$

5-7 Some Particular Forces

- **Gravitational force :** $\vec{\mathrm{F}}_{\mathrm{g}}$ on a body is a pull by another body (In most situations, the other body is earth).

  $\vec{\boldsymbol{F}}_{\boldsymbol{g}} = \boldsymbol{m}\vec{\boldsymbol{g}}$: The force is directed down toward the ground.

- **The weight, W:** Is the magnitude of the upward force needed to balance the gravitational force on the body.

$$\boldsymbol{W} = \boldsymbol{mg}$$

- **Normal force, $\vec{\mathbf{F}}_{\mathbf{N}}$** : Is the force on a body from a surface against which the body presses. $\vec{\mathrm{F}}_{\mathrm{N}}$ is always perpendicular to the surface.

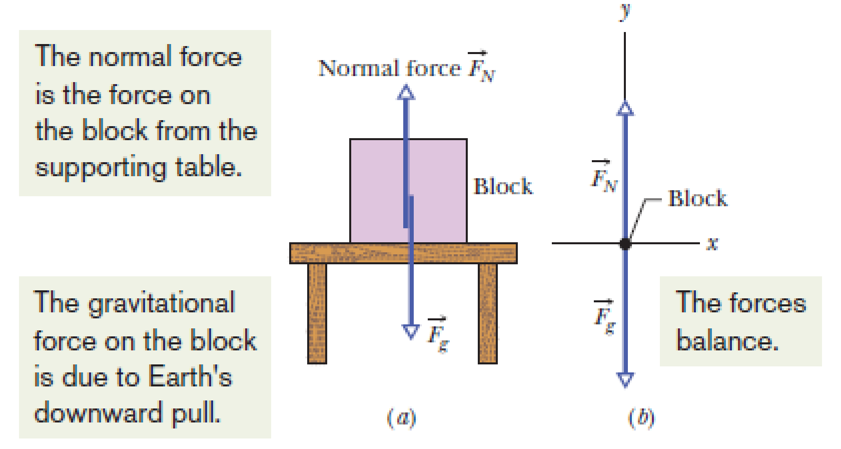

The normal force is the force on the block from the supporting table.
The gravitational force on the block is due to Earth's downward pull.
Normal force $\vec{F}_N$
Block
$\vec{F}_g$
(a)
y
$\vec{F}_N$
Block
x
$\vec{F}_g$
The forces balance.
(b)

Fig. 5-7 (*a*) A block resting on a table experiences a normal force $\vec{F}_N$ perpendicular to the tabletop. (*b*) The free-body diagram for the block.

- **Frictional force, $\vec{f}$** : Is the force on a body when the body slides or attempts to slide along a surface.

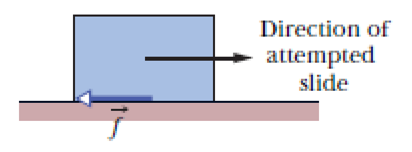
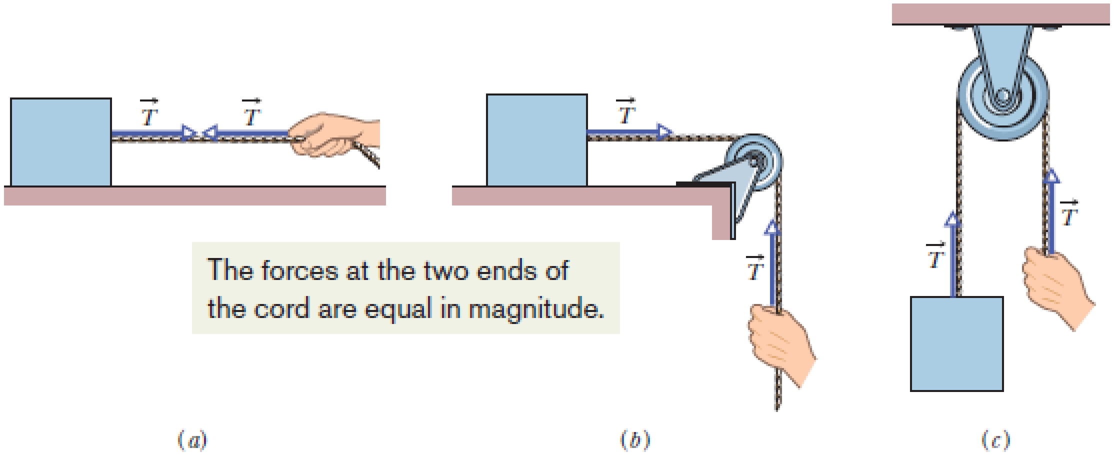


Fig. 5-8 A frictional force $\vec{f}$ opposes the attempted slide of a body over a surface.

- **Tension, $\vec{T}$** : When a cord is under tension, each end of the cord pulls on a body. The pull is directed along the cord, away from the point of attachment to the body.



The forces at the two ends of the cord are equal in magnitude.

Fig. 5-9 (*a*) The cord, pulled taut, is under tension. If its mass is negligible, the cord pulls on the body and the hand with force $\vec{T}$, even if the cord runs around a massless, frictionless pulley as in (*b*) and (*c*).

5-8 Newton's Third Law

- Two bodies are said to interact when they push or pull on each other.

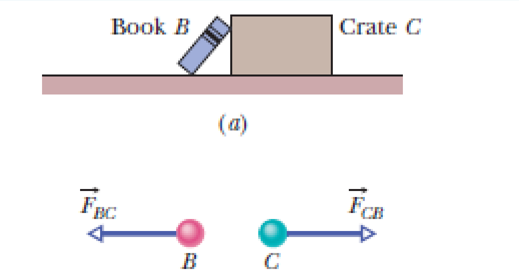
- **Newton's Third Law :** When two bodies interact, the forces on the bodies from each other are always **equal in magnitude and opposite in direction**.

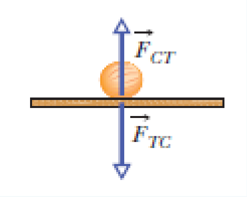
- For the book and crate, we can write this law as the scalar relation

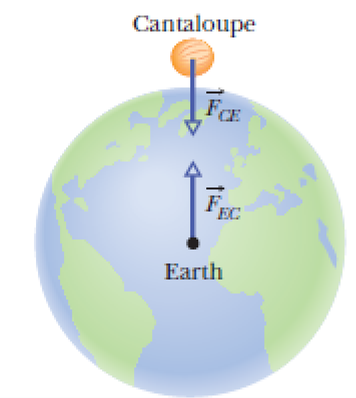
$$\boldsymbol{F_{BC} = F_{CB}}$$

Or as the vector relation

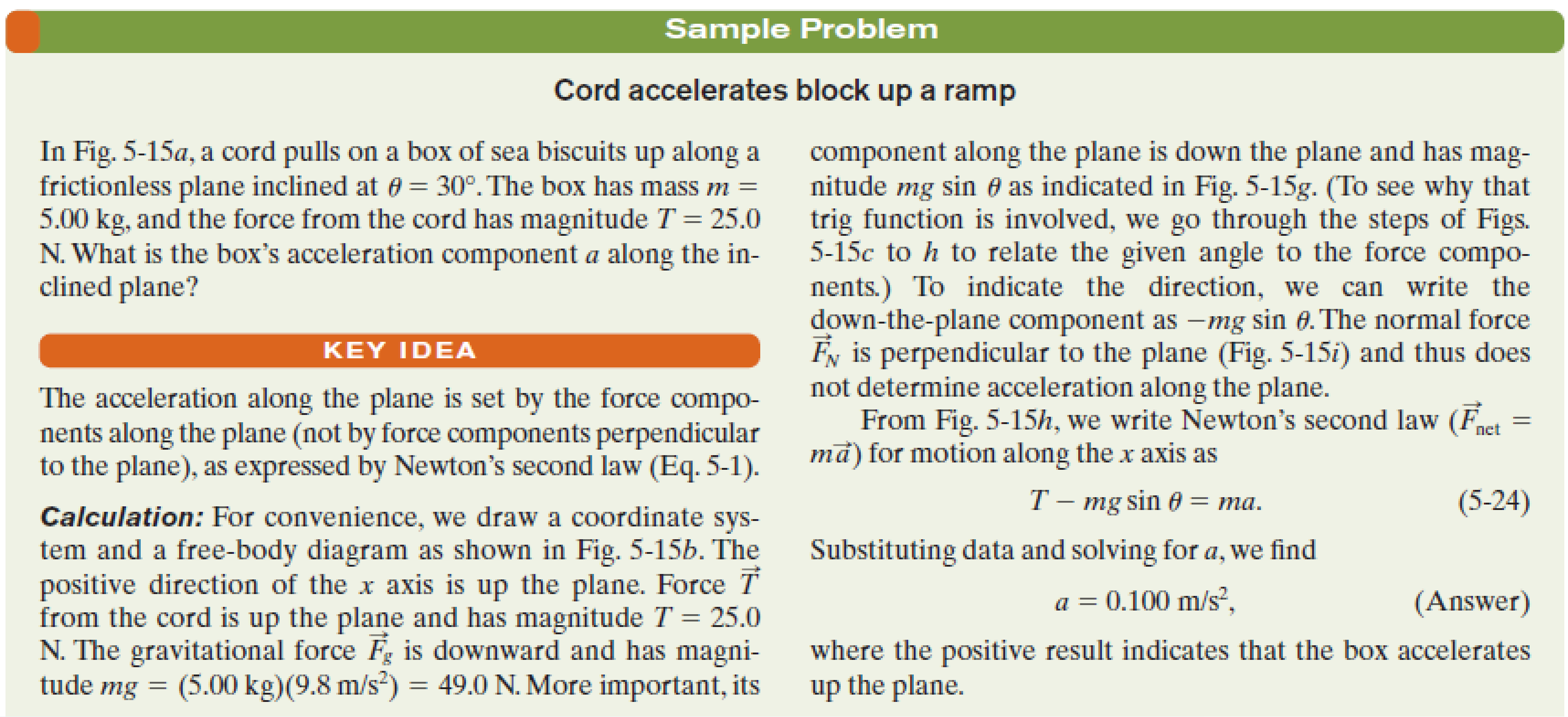
$$\vec{\boldsymbol{F}}_{\boldsymbol{BC}} = -\,\vec{\boldsymbol{F}}_{\boldsymbol{CB}}$$







5-9 Applying Newton's Laws



Sample Problem

Cord accelerates block up a ramp

In Fig. 5-15*a*, a cord pulls on a box of sea biscuits up along a frictionless plane inclined at $\theta = 30°$. The box has mass $m = 5.00$ kg, and the force from the cord has magnitude $T = 25.0$ N. What is the box's acceleration component a along the inclined plane?

KEY IDEA

The acceleration along the plane is set by the force components along the plane (not by force components perpendicular to the plane), as expressed by Newton's second law (Eq. 5-1).

Calculation: For convenience, we draw a coordinate system and a free-body diagram as shown in Fig. 5-15*b*. The positive direction of the x axis is up the plane. Force $\vec{T}$ from the cord is up the plane and has magnitude $T = 25.0$ N. The gravitational force $\vec{F}_g$ is downward and has magnitude $mg = (5.00 \text{ kg})(9.8 \text{ m/s}^2) = 49.0$ N. More important, its component along the plane is down the plane and has magnitude $mg \sin\theta$ as indicated in Fig. 5-15*g*. (To see why that trig function is involved, we go through the steps of Figs. 5-15*c* to *h* to relate the given angle to the force components.) To indicate the direction, we can write the down-the-plane component as $-mg \sin\theta$. The normal force $\vec{F}_N$ is perpendicular to the plane (Fig. 5-15*i*) and thus does not determine acceleration along the plane.

From Fig. 5-15*h*, we write Newton's second law ($\vec{F}_{\text{net}} = m\vec{a}$) for motion along the x axis as

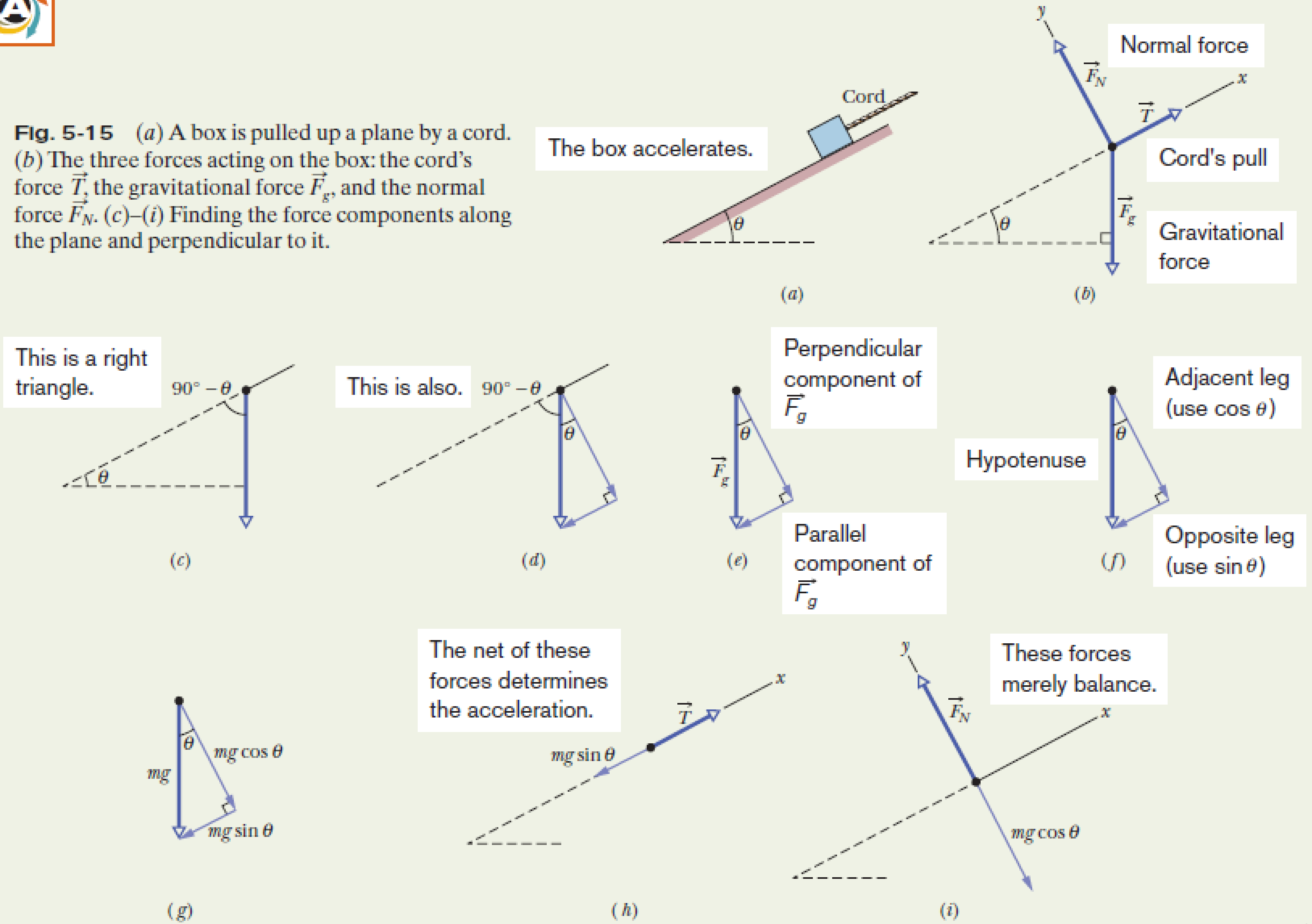
$$T - mg \sin\theta = ma. \tag{5-24}$$

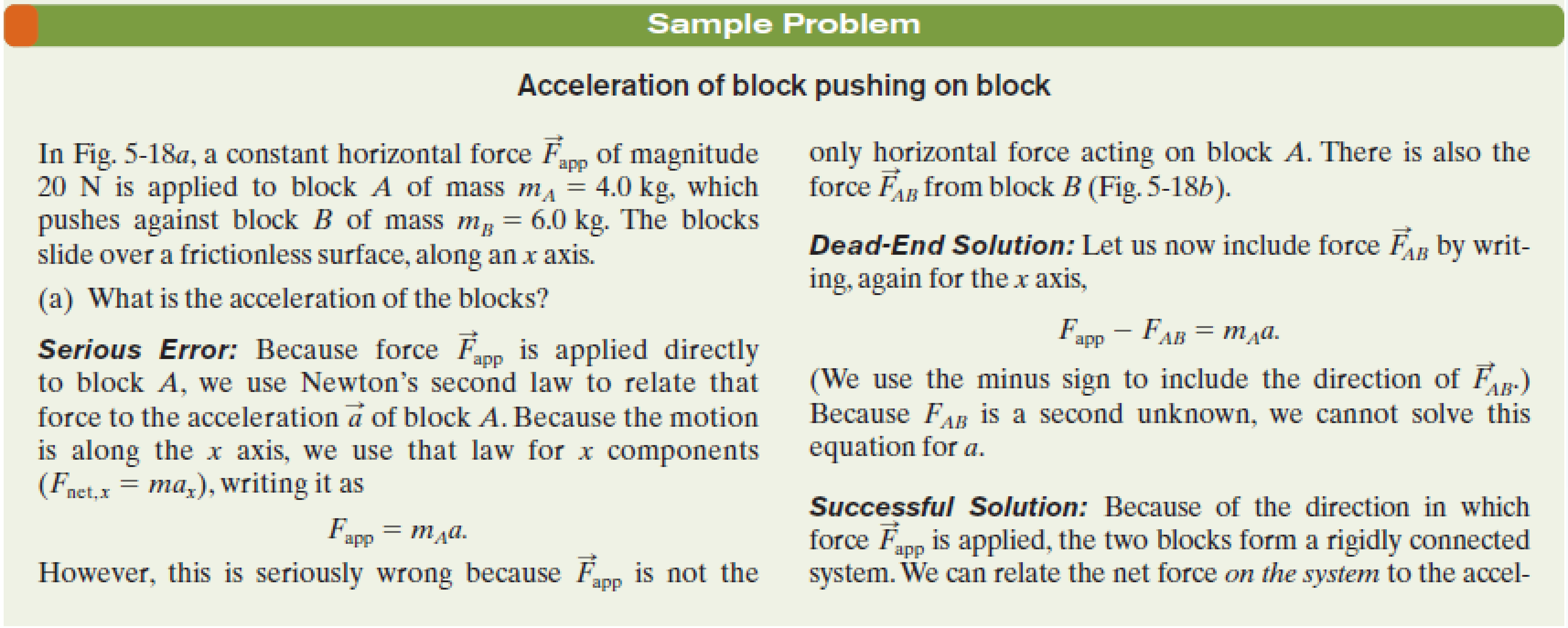
Substituting data and solving for a, we find

$$a = 0.100 \text{ m/s}^2, \quad \text{(Answer)}$$

where the positive result indicates that the box accelerates up the plane.

Fig. 5-15 (*a*) A box is pulled up a plane by a cord. (*b*) The three forces acting on the box: the cord's force $\vec{T}$, the gravitational force $\vec{F}_g$, and the normal force $\vec{F}_N$. (*c*)–(*i*) Finding the force components along the plane and perpendicular to it.





Sample Problem

Acceleration of block pushing on block

In Fig. 5-18*a*, a constant horizontal force $\vec{F}_{app}$ of magnitude 20 N is applied to block *A* of mass $m_A = 4.0$ kg, which pushes against block *B* of mass $m_B = 6.0$ kg. The blocks slide over a frictionless surface, along an *x* axis.

(a) What is the acceleration of the blocks?

Serious Error: Because force $\vec{F}_{app}$ is applied directly to block *A*, we use Newton's second law to relate that force to the acceleration $\vec{a}$ of block *A*. Because the motion is along the *x* axis, we use that law for *x* components ($F_{net,x} = ma_x$), writing it as

$$F_{app} = m_A a.$$

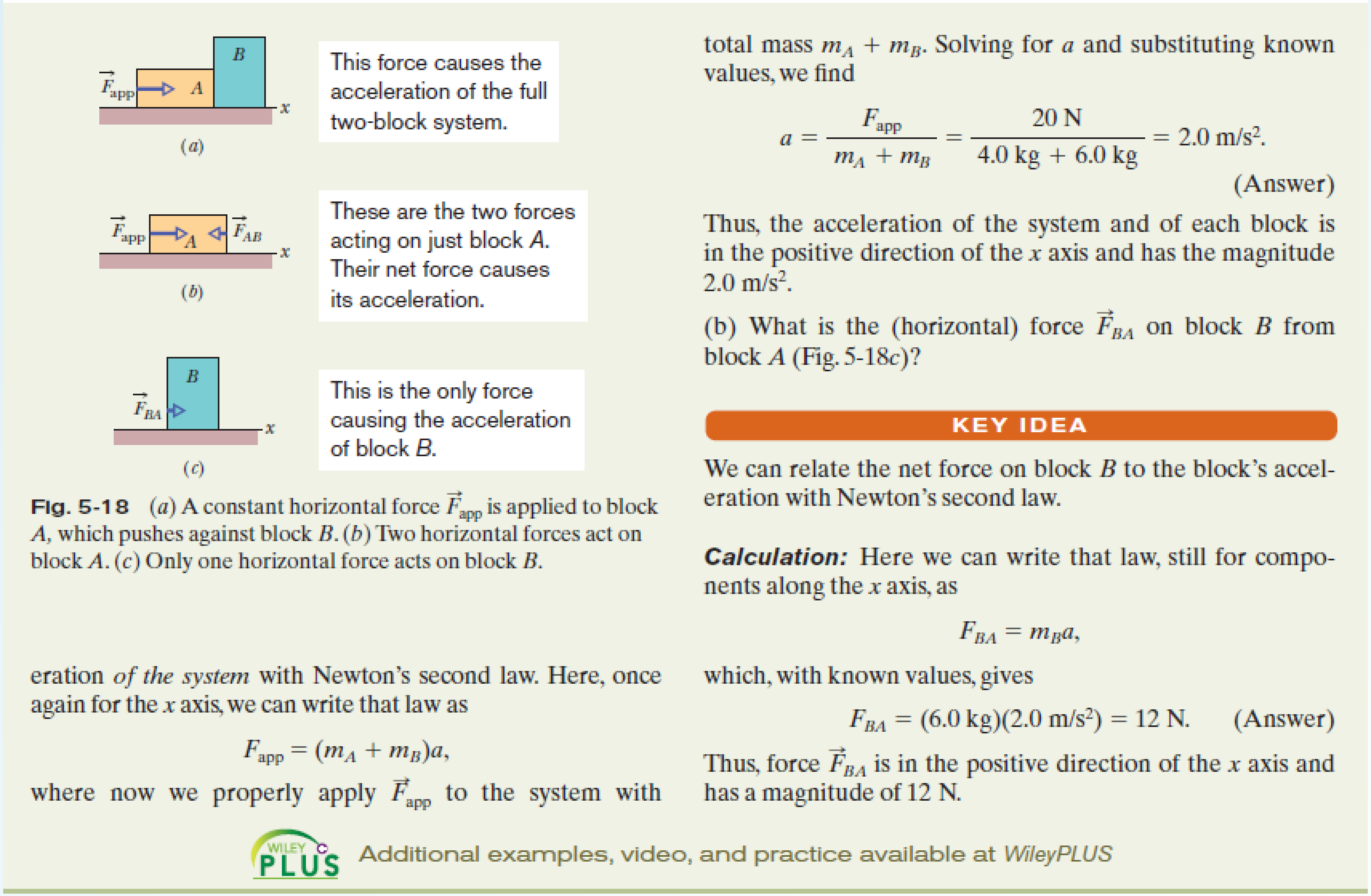
However, this is seriously wrong because $\vec{F}_{app}$ is not the only horizontal force acting on block *A*. There is also the force $\vec{F}_{AB}$ from block *B* (Fig. 5-18*b*).

Dead-End Solution: Let us now include force $\vec{F}_{AB}$ by writing, again for the *x* axis,

$$F_{app} - F_{AB} = m_A a.$$

(We use the minus sign to include the direction of $\vec{F}_{AB}$.) Because F_{AB} is a second unknown, we cannot solve this equation for a.

Successful Solution: Because of the direction in which force $\vec{F}_{app}$ is applied, the two blocks form a rigidly connected system. We can relate the net force *on the system* to the accel-



This force causes the acceleration of the full two-block system.

These are the two forces acting on just block *A*. Their net force causes its acceleration.

This is the only force causing the acceleration of block *B*.

Fig. 5-18 (*a*) A constant horizontal force $\vec{F}_{app}$ is applied to block *A*, which pushes against block *B*. (*b*) Two horizontal forces act on block *A*. (*c*) Only one horizontal force acts on block *B*.

eration *of the system* with Newton's second law. Here, once again for the *x* axis, we can write that law as

$$F_{app} = (m_A + m_B)a,$$

where now we properly apply $\vec{F}_{app}$ to the system with total mass $m_A + m_B$. Solving for *a* and substituting known values, we find

$$a = \frac{F_{app}}{m_A + m_B} = \frac{20 \text{ N}}{4.0 \text{ kg} + 6.0 \text{ kg}} = 2.0 \text{ m/s}^2. \qquad \text{(Answer)}$$

Thus, the acceleration of the system and of each block is in the positive direction of the *x* axis and has the magnitude 2.0 m/s^2.

(b) What is the (horizontal) force $\vec{F}_{BA}$ on block *B* from block *A* (Fig. 5-18*c*)?

KEY IDEA

We can relate the net force on block *B* to the block's acceleration with Newton's second law.

Calculation: Here we can write that law, still for components along the *x* axis, as

$$F_{BA} = m_B a,$$

which, with known values, gives

$$F_{BA} = (6.0 \text{ kg})(2.0 \text{ m/s}^2) = 12 \text{ N}. \qquad \text{(Answer)}$$

Thus, force $\vec{F}_{BA}$ is in the positive direction of the *x* axis and has a magnitude of 12 N.

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